Appendix E
Description and Use of Instruments During Earth and Rock-Fill Dam Construction

E-1. General

Stability of an earth and rock-fill dam is often more uncertain during construction than upon completion. Unfavorable conditions produced, for example, by inclement weather during construction may result in transient conditions of marginal stability, which may be the most dangerous over the life of an embankment. For that reason, it is important to carefully and continuously monitor the state of a compacted earth structure during construction. Instruments to monitor displacement, slope (change), pore water pressure, soil stress, and water flow are necessary to monitor changes in an embankment that may signify the onset of instability and indicate the need of a change in construction technique or procedure. The basic instruments, their function and basic operating principal will be described here. However, EM-1110-2-1908 is under preparation at this writing and will clarify the philosophy, policy, use, and installation of instrumentation with respect to earth and rock-fill dams.

E-2. Displacement Measuring Techniques and Instruments

a. Slope indicators (inclinometers). Slope indicators are used primarily to monitor earth movement in undisturbed soil masses as well as compacted embankments by detecting changes in slope within the soil structures. A specially designed plastic or aluminum casing with an alignment groove along one edge may be installed in a bore hole up to 900 ft deep. Slope indicator instruments are lowered into the casings on spring-loaded rollers which ride into the grooves to maintain alignment. Deviation from the vertical is detected by monitoring an electronic signal from either a Wheatstone Bridge circuit or piezoelectric crystals within the sensor, which is generated by a change in stress in a mechanical system such as a pendulum or cantilever arm. Slope versus electronic signal from a slope indicator instrument is established by calibration; therefore the slope of the bore hole with depth is determined from the output signal of the sensor as it is lowered into the bore hole. Change in slope with time is an indication of embankment movement. Plots of slope versus depth at various locations over the site of the embankment will indicate patterns of movement and will therefore index the stability of the embankment. Manufacturers of slope indicator instruments claim that some models have the sensitivity to detect a deviation in slope of one part in 10,000. A careful calibration is recommended before installation of this or any instrument to confirm that devices are operational, and that they deliver the measurement accuracy required for proper monitoring.

b. Settlement/heave measurement devices. Settlement devices are sometimes used in the same casings as slope indicators. Settlement meter casings are designed to “telescope” in order to follow settlement or heave within the soil structure. Special couplings in the casing may allow from 6 to 12 in. of movement per casing section. A probe which hooks to the bottom lip of a casing section is lowered into the bore hole. After hooking onto the bottom lip of a casing section, distance from the top of the casing is measured with a surveyor’s chain. The elevation of the casing top may be determined by standard level survey techniques based on bench marks outside the settlement zone. Calibration required for this procedure is accomplished with a surveyor’s chain. A slight variation to this procedure is to measure settlement in emplaced structures by placing ferrous metal washers around the casings. The vertical position of the washers may be monitored using magnetic or inductive pickup sensors.

E-3. Stress Measurement

a. Carlson soil stress meters. These instruments are designed for the direct measurement of soil pressure against a solid structure. The meter consists of two steel discs connected along their circumferences/edges by a flexible rim. A thin film of mercury fills the space between the discs. When subjected to stress, the mercury deflects an internal diaphragm. The device is calibrated in a pressure chamber under hydrostatic pressure such that a relationship between pressure and diaphragm deflection is established. When implanted in a soil structure, the stress pattern over the area/face of the meter is averaged. The Carlson soil stress meter is usually placed next to a solid structure with its top side exposed to soil. In such an installation, the flexible rim is covered with neoprene rubber to prevent binding and damage to the instrument.

b. Flat jacks. These stress measurement devices are variations of the Carlson soil stress meter and consist, essentially, of a fluid-filled space between two flat parallel plates with a pressure-tight hinged seal around the periphery. These instruments are permanently installed in structures of interest at the desired location and orientation. The average pressure exerted by the soil on the face of the jack is transmitted to the fluid inside, which is measured electronically or mechanically. The main advantage of these devices is that they require little deformation for activation; the main disadvantage is that their stiffness may not match that of the structure in which they are installed and, as a result, the stress measured may be in error. Calibration of these devices can be difficult, and installation must be performed by an experienced technician.

E-4. Pore Pressure Measurement

Piezometers are instruments permanently installed in a soil or rock structure to measure fluid pressure. Several types of piezometers based on different pressure sensing mechanisms are available for general use. Each type will be identified and the operating mechanism briefly described.

a. Open standpipe piezometer. This type of device consists of an open tube in which the level of fluid is measured by sounding, or by lowering a tape into the tube to measure the water level.

b. Casagrande piezometer. The tip of the device consists of a 2-ft-long porous tube connected to a riser pipe of 3/8-in. tubing. Water level (pressure) is measured with an electronic sounding device or a pressure gauge if the water level is higher than the ground surface.

c. Wellpoint piezometer. The instrument consists of a perforated tip (well screen, epoxied sand filter, well strainer, etc.) connected to a standpipe. Water level is measured by lowering a sounding device into the standpipe.

d. Hydraulic piezometer. Two designs are in general use: the USBR device and the Bishop device. This type of piezometer consists of two tubes leading to the tip, which contains a porous element common to the two tubes. The tip must be de-aired for proper operation; de-airing is accomplished by flushing water through one tube and bleeding through the other until saturation is achieved. One tube is then shut off and the other connected to a vacuum/pressure gauge which reads fluid level directly.

e. Diaphragm piezometers. Two designs are in general use: the Warlan device and the Gloetzl device. The diaphragm piezometer consists of two tubes leading to the piezometric porous tip. A membrane is forced against the end of one of the tubes by in situ water pressure. To make pore pressure measurement, from the observation station, air pressure is introduced into the tube that has the membrane against it until the pore pressure acting on the opposite side is slightly exceeded, allowing air past the membrane flapper. This air, escaping through the opposite tube, is detected with a bubble chamber at the observation station. The air pressure is then reduced until bubbling stops, at which time the air pressure in the line is assumed to equal the pore water pressure.

f. Electronic strain gauge piezometers. The Carlson piezometer and electronic pressure transducers are examples of this design of piezometer. The principal of operation is that water pressure deflects a diaphragm which has been strain-gauged or otherwise fitted for electronic displacement measurement. Pressure versus strain meter reading is established by calibration so that pore water pressure is determined directly by a meter reading.

g. Vibrating wire piezometers. Mechanical resonance or vibrating wire transducers are sometimes used to measure water pore pressure. In these instruments, a wire under tension is connected to (the center of) a diaphragm which deflects as the result of water pressure. Deflection of the membrane changes the tension in the wire and therefore the resonant frequency of the structure. The system is configured so that the wire under tension may be excited to resonance by a magnetic coil and the resonant frequency measured electronically. The relationship between resonant frequency and pressure is established by calibration. Vibrating wire piezometers are essentially like electronic strain gauge transducers except that the internal displacement, or strain associated with pressure change is measured using electromechanical means.

E-5. Flow Measurement

Flow measurement associated with dam construction may be achieved using two basic devices, weirs and impeller flow transducers. Each will be briefly described.

a. Weirs. A weir is an obstruction in a channel that causes water to back up behind it and to flow over or through it. By measuring the height of the upstream water surface, the rate of flow is determined. Weirs constructed from a sheet of metal or other material such that the jet, or nappe, springs free as it leaves the upstream face are called sharp-crested weirs. For example, the V-notch weir is a very effective and widely used sharp-crested weir which may be calibrated quite precisely and reliably for use in flow measurement. Other weir types, such as the broad-crested weir, support water flow in a longitudinal direction. The relationship between flow rate versus height above the crest of a particular weir is established by calibration against a standard with known volume discharge characteristics.

b. Impeller flow transducers. The impeller flow transducer consists of a flow chamber around an impeller shaft and rotor. As fluid flows through the chamber, it impinges on the blades to cause rotation of the impeller shaft, the speed of which is measured electronically with an encoder. A relationship between quantity of flow and shaft rotation speed/electronic output may be established by calibration. Impeller flow transducers are generally used to measure relatively small rates of flow which must be obtained precisely. However, impeller flow transducers do not work well when used with water containing sediment, as particles of grit tend to jam the mechanism, causing it to seize.

E-6. Temperature Measurement

One possible benefit of temperature measurement connected with dam construction is that it may aid in determining the source of seepage or leakage water. Temperature measurement sensors may be permanently installed in a compacted earth structure during construction or may be mobile and simply lowered into boreholes for spot temperature checks. Two electronic devices are generally used for temperature measurement, the thermocouple and the thermistor. The mercury thermometer is also useful. Each will be briefly described.

a. Thermocouples. A thermocouple is an electronic circuit consisting of two dissimilar metals in which a voltage is produced when two junctions of the metals are at different temperatures. For example, the temperature of ice water is typically used as a reference junction temperature and the voltage produced by the opposite junction calibrated versus temperature (of that junction). In many commercial thermocouple instruments, the function of the reference junction is simulated electronically. For the temperature range expected in earth dam construction, copper/constantan or iron/constantan thermocouples (commonly called ISA[1] J-type or T-type thermocouples, respectively) will be most appropriate and useful.

b. Thermistors. A thermistor is a composite semiconductor that has a large negative temperature coefficient of resistance and, as such, can be used for temperature measurement. The electronic circuit associated with a thermistor is designed to measure the resistance of the thermistor and, therefore, the temperature-resistance characteristics of the device must be established by calibration. The electronic circuitry associated with thermistors is often designed to produce readings directly in engineering temperature units.

c. Mercury thermometer. A mercury thermometer is a closed evacuated glass tube containing a quantity of mercury. Mercury has a relatively high coefficient of temperature expansion, and when the tube is placed in a temperature environment, the mercury will expand to fill a given portion of the tube. The tube is graduated, and the relationship between temperature and the expansion of the mercury in the tube as quantified by graduations on the tube is established by calibration. The mercury thermometer is very easy to use and relatively precise; however, because of the fast time response of thermal expansion of mercury, the device must be used only in applications when the tube may be observed directly (that is, it may not be lowered into boreholes).

E-7. Strong Motion Monitoring

Strong motion monitoring is used to measure the response of an embankment dam to seismic activity. The most important benefit obtained is to guide decisions on inspection and repair after the structure has been subjected to a seismic event. The information may be used to determine if the event was larger or smaller than the design earthquake and to decide what repair or strengthening is needed. Instruments for strong motion monitoring are called strong motion accelographs of seismographs. The key element of the instrument is an accelerometer, which consists of a mass suspended in a case. The case itself is securely fastened to the dam. During an earthquake, relative movement between the mass and the case is converted to an electrical signal which is converted to either the acceleration or the velocity of the ground motion. An accelograph also contains signal amplifiers, a recording device such as paper, photographic film, or magnetic tape, along with a rechargeable battery power supply, a very accurate clock, and a motion trigger to turn on the instrument when a predetermined level of ground motion is exceeded. An important consideration in the design and installation of such instruments is that they be sensitive enough to give an accurate account of the motion, yet be protected so that they are not damaged during the event.

[1] Instrument Society of America.

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